ACOUSTIC EMISSION MONITORING OF THIN PLY HYBRID COMPOSITES UNDER REPEATED QUASI-STATIC TENSILE LOADING

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ABSTRACT. This paper investigates the applicability of the acoustic emission (AE) technique for identification of the damage onset and accumulation in S-Glass/TR30-Carbon hybrid laminates under repeated quasi-static tensile loading. The samples were made of 2 layers of unidirectional thin carbon prepreg plies which were sandwiched between 2 standard thickness S-glass prepreg plies. Analysis of the AE results shows that there are two types of events regarding the AE parameters; those with high values of energy and amplitude, and low values which are assumed to be related to the fragmentation of the carbon layer and delamination of the carbon/glass interface, respectively. There are more friction related AE signals during the unloading stage than the loading stage due to collision and rubbing between existing crack faces. Increasing the strain level increases the number of fragmentations and the AE technique is able to quantify this. It is concluded that the AE technique can be used to evaluate the number of fragmentations and can identify the damage evolution of the hybrid laminate under repeated quasi-static tensile loading.

KEYWORDS: Carbon/glass hybrid, Pseudo ductility, Acoustic emission, Fragmentation.

1. INTRODUCTION

Glass/carbon hybrid composite materials have been studied to create pseudo-ductility in order to address the lack of ductility in composite laminates [1-3]. In those studies, it was observed that the damage modes causing pseudo-ductile behaviour in thin-ply UD carbon/S-Glass laminates were carbon ply fragmentation and stable delamination of the carbon/glass interface.

Characterising the failure mechanisms which have introduced pseudo-ductility can be useful to optimise the design of more general layups. Acoustic emission (AE) as an online monitoring technique has good potential to identify active damage mechanisms.

The AE technique is the phenomenon of radiation of transient elastic waves (acoustic events) released by a sudden redistribution of stress in a material due to crack formation, plastic deformation, etc. This technique has been used by different researchers for damage characterisation of composite materials. Successful results have been reported for damage characterization of composite laminates using the AE parameters. The results showed that the amplitude, energy and frequency ranges of different damage modes were different from each other [5-6].

In our previous work, the AE technique was found to be an applicable method to characterise the damage mechanisms in thin-ply UD carbon/S-Glass laminates under tension loading [7]. The AE events were correlated to direct observations of the corresponding damage mechanisms using the energy and the amplitude of the AE events.

The aim of this study is to investigate the applicability of the AE technique for identification of the damage onset and accumulation in S-Glass/TR30-Carbon hybrid laminates under repeated quasi-static tensile loading. To achieve this goal, thin-ply hybrid materials were subjected to repeated quasi-static tensile loading and the generated failure mechanisms were monitored using the AE technique.

2. Experimental

2.1. Materials

The materials considered in this study are thin carbon/epoxy prepreg and standard thickness glass/epoxy prepreg. Table 1 gives more information on the characteristics of the prepregs. The high strain material of the hybrid laminate is UD S-glass/913 epoxy prepreg supplied by Hexcel. The low strain material is a thin carbon prepreg from SK Chemicals (South Korea) under the trade name of SkyFlex USN020A. The carbon fibres in the thin USN020A prepreg are Pyrofil TR 30 made by Mitsubishi Rayon with the modulus and fibre failure strain given in Table 1. The corresponding matrix is SK Chemical's type K50 epoxy resin.

Table 1. Characteristics of the prepregs and fibres used.

Prepreg type	S-glass/epoxy	TR30/epoxy
Fibre modulus E (GPa)	88	234
Fibre failure strain (%)	5.5	1.9
Cured nominal thickness (mm)	0.155	0.029
Fibre mass per unit area (g/m2)	190	21.2
Fibre volume fraction (%)	50	41

2.2. Specimen design and manufacturing

The hybrid plate was laid up in the sequence of $[G_1/C_2/G_1]$ where G stands for S-glass plies and C for TR30 carbon plies. The benefit of using glass prepreg was that it is translucent, allowing crack and delamination detection visually.

Since characterization of different damage types was the aim of this paper, the lay-up was chosen to have a combination of damage modes, i.e. both fragmentation in the carbon layer and stable delamination. Different possible failure modes for different relative and absolute carbon layer thicknesses are illustrated in the damage mode map [3] in Figure 1. The damage mode map shows that this configuration results in the combined fragmentation and dispersed delamination failure mode.

The laminate was cured in an autoclave with the recommended cure temperature and pressure cycle for the Hexcel 913 resin (60 min@125 ºC, 0.7 MPa). Fabrication of the specimens was done using a diamond cutting wheel. Good integrity of the hybrid laminates was confirmed during test procedures and no phase separation was observed on cross sectional micrographs.

2.3. Test procedure

Repeated quasi-static tests were carried out using a computer controlled Instron 8801 type 100 kN rated universal hydraulic test machine with wedge type hydraulic grips. A 25 kN load cell was attached for better resolution in the expected load range. The test was conducted under displacement control at a cross-head speed of 2 mm/min for both the loading and unloading phases, with immediate reloading. Seven cycles were chosen, each with a certain displacement limit, after which the load returns to zero. The nominal specimen dimensions for the tests were 240/160/20/h mm overall length/free length/width/variable thickness respectively. 8 specimens were tested. To measure the strains an Imetrum video gauge system was used, tracking the points applied on the specimen face using points over a particular gauge length. An AE data acquisition system (PAC) PCI-2 with a maximum sampling rate of 40 MHz was used to record the AE signals. Two PAC R15 resonant-type, broadband, single-crystal piezoelectric transducers were used as AE sensors to monitor the damage events. The frequency range of the sensors was 20–900 kHz, and the gain selector of the preamplifier and the threshold value were set to 40 dB. The test sampling rate was 5 MHz.

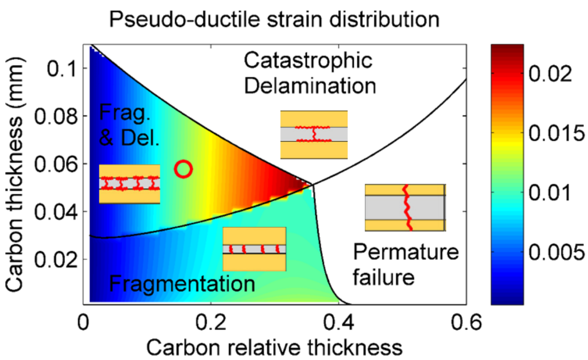

Figure 1. Distribution of pseudo-ductile strain for [G1/C2/G1] laminates made with 2 plies of TR30 carbon prepreg.

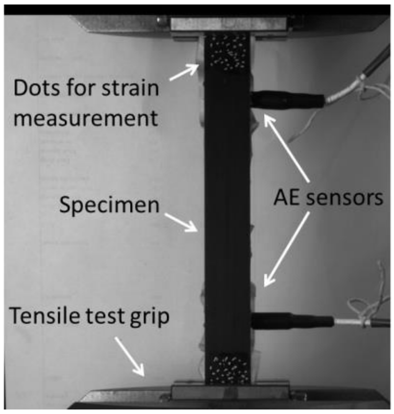

Figure 2. Schematic of the experimental setup.

3. Results and discussion

Figure 3 shows a typical load-strain curve for repeated quasi-static tensile tests of the investigated layup. The chosen strains, calculated from the video gauge were: C1: 1.33 %, C2: 1.63 %, C3: 1.89 %, C4: 2.07%, C5: 2.32%, C6: 2.71 %, and C7: 3.12 %, where C stands for "Cycle". Until the third cycle, the applied strain is lower than the failure strain of the carbon layer (i.e. 1.9 %) and there is an appearance of a plateau in the fourth cycle, which then evolved in the other cycles. After the third cycle, there is a residual strain or permanent deformation at zero load and by increasing the strain level the initial tensile modulus decreases. The important factor responsible for the changes in the stress-strain diagram is the occurrence of the carbon ply fragmentation and delamination of the carbon/glass interface.

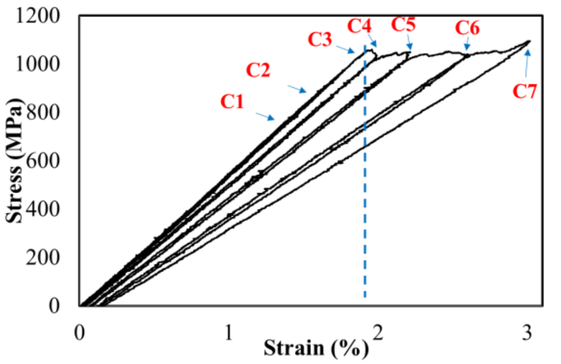

Figure 3. a) Stress-strain curve for a typical specimen. specimen subjected to cyclic loading. The dashed line corresponds to the damage initiation.

In order to extract more useful information about the damage mechanisms of the tested specimens, the AE technique was used. A previous study reported that it is possible to characterise certain mechanisms by studying the energy and the amplitude of the AE events during the damage accumulation [7]. It is concluded that higher amplitudes and energies represent fibre fragmentations, medium values are mostly in connection with delamination, while the lower ones are noise. It was found that delamination between the carbon/glass interface occurred between 60-85 dB amplitude and 30-800 aJ energy, while these values were 75-100 dB and 800-65000 aJ in the case of carbon fibre fragmentation.

Applying this classification technique, the recorded events were separated into three clusters. The results are illustrated in Figures 4 and 5. As illustrated, the damage mechanisms are identified by the AE events with different energy and amplitude levels. The clear and significant AE events start when the plateau on the stress-strain curve begins. There are also some fragmentation and delamination related events before cycle 4 due to the relaxation of the internal stresses developed due to issues such as free fibres at the edges of the specimens.

Higher intensity AE signals appear around the peak loads, whereas the lower energy and amplitude signals can be found when unloading the sample as well as between the load peaks. The lower intensity signals, i.e. the noise, could be friction due to existing damage mechanisms. There are more noise related AE signals during the unloading stage than the loading stage.

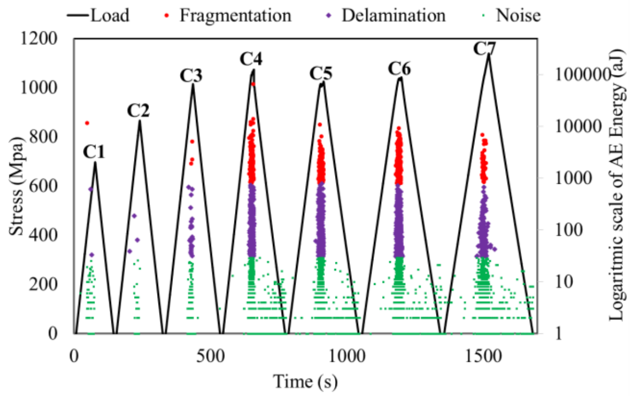

Figure 4. Stress-time and AE event energy distribution for a typical specimen.

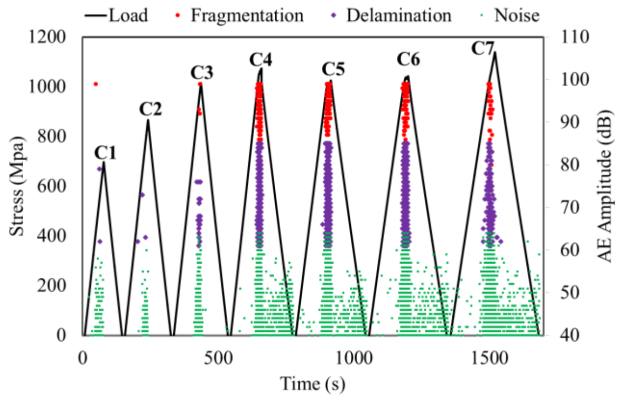

Figure 5. Stress-time and AE event amplitude distribution for a typical specimen.

Cumulative AE energy of the AE signals is shown in Figure 6. Before reaching the failure strain of the carbon layer, i.e. in cycles 1, 2 and 3, there is no significant increase in the cumulative AE trends. After that, in each cycle, there is significant increase. Between the peaks, the rate of damage accumulation stays relatively constant. Fragmentation associated signals have much higher cumulative energy than the delamination associated ones. The noise signals occur continuously with some small steps near the peak stresses which could have been caused by reflection of high energy signals or more friction related events.

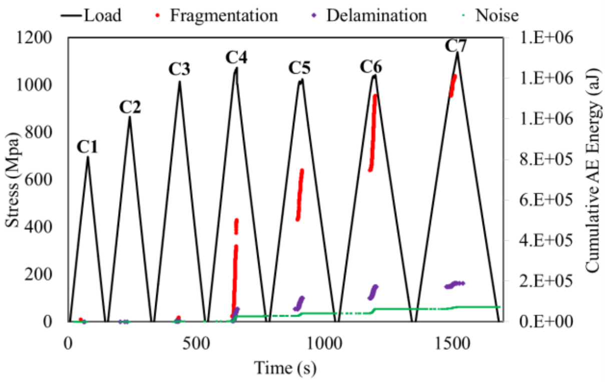

Figure 6. Cumulative AE event energy for each class of AE signal for a typical specimen.

Each AE event is regarded as one damage event. The number of damage events is illustrated in Figure 7. This number is 495 for the fragmentation events prior to the final peak point and the average energy content for each fragmentation is 2445 aJ.

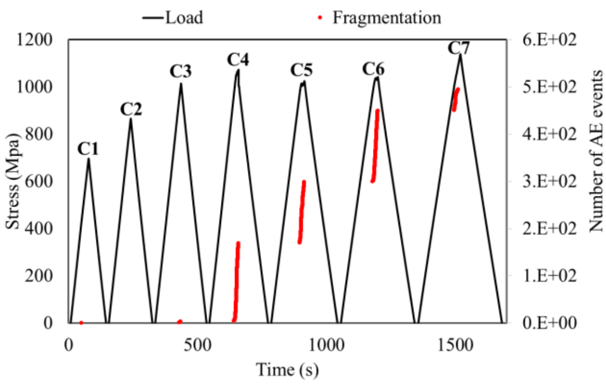

Figure 7. Number of fragmentation type AE events for a typical specimen.

4. Conclusions

In this paper, the AE technique is utilised to identify the damage modes in thin-ply UD carbon/glass hybrid laminates under repeated quasi-static tensile loading. Carbon ply fragmentation and delamination of the carbon/glass interface are found to be the main damage sources for the AE signals. It is concluded that the AE technique can be used to evaluate the number of fragmentations and can identify the damage evolution of the hybrid laminate under repeated quasi-static tensile loading. The proposed method is very useful as an effective way to accurately detect fibre fragmentation, as well as to track its evolution and accumulation in more complex loading cases such as cyclic loading.

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